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Rotorwash Wind Sensor Evaluation

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16. Abstract

This project's purpose was to assess and document the ability of the Qualimetrics, Inc. model 2132 wind sensor (a cup and vane type sensor) to measure a rotorwash flow field as compared to the TSI, Inc. model 204D ion beam deflection sensor. The tests concentrated on the sensor's ability to capture dynamic characteristics of a helicopter rotorwash flow field. The project was conducted from April to November 1992 and consisted of quantitative laboratory and field testing. The laboratory testing included 9.5 hours of wind tunnel test time, subjecting each sensor to three step input tests at velocities of 20 knots, 50 knots, and 80 knots. Field test data were collected during one hour of SH-60B helicopter hover time at heights of 15 and 25 feet above ground level at distances of 35 and 70 feet from the wind sensors. Aircraft gross weights ranged between 19,600 and 20,500 pounds. All field test data were obtained in ambient wind conditions of approximately 8 knots at 40 degrees relative to the aircraft nose, -40 feet pressure altitude in an ambient temperature of 85°F.

Laboratory data analysis indicates the model 2132 cup and vane sensor's time constant values were significantly higher than those of the model 204D ion beam sensor and varied relative to wind tunnel velocity settings. This indicates the model 2132 sensor's ability to accurately capture oscillations in a dynamic flow field is significantly less than the model 204D sensor. The model 2132 sensor did detect periodic or pulsating velocity magnitudes, but failed to capture significant oscillations as compared to the model 204D sensor. Comparative analysis of all field test event data indicate the model 2132 sensor only detected frequencies below 1.5 Hz and only captured an average of 46% of the model 204D sensor's maximum amplitude pulse values that were below 1.5 Hz. The model 2132 sensor's inability to capture many of the maximum pulse amplitudes is evidence of the sensor's limited capability to capture velocity magnitude variations in a dynamic flow field.

The model 2132 cup and vane sensor's average and minimum velocities for each test event were significantly higher than the model 204D ion beam sensor's values. This is additional evidence that the model 2132 sensor is slower to respond to rapid changes in a dynamic flow field. Compared to the TSI, Inc. model 204D ion beam sensor, the Qualimetrics, Inc. model 2132 cup and vane sensor failed to measure accurately a rotorwash flow field in terms of frequency, amplitude, frequency content, and velocity magnitude and thus is not recommended for helicopter rotorwash velocity data collection.

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INTRODUCTION

BACKGROUND

1. The NAVAIRWARCENACDIV Patuxent River, Systems Engineering Test Directorate's Aircrew Systems Department (ASD) is nationally recognized by industry and government for its expertise in aircraft downwash velocity measurement, measurement technology, test methodology, analysis and reporting and has the responsibility of conducting evaluations on military aircraft programs. Current measurement capabilities rely on the TSI model 204D two axis ion beam deflection sensor, which is considered to be one of the best instruments for accurately measuring aircraft downwash velocity. The Federal Aviation Administration (FAA) Technical Center located in Atlantic City, New Jersey, has a similar requirement to evaluate civil aircraft rotorwash. The FAA has procured the Qualimetrics, Inc. model 2132 Combination Wind Speed and Wind Direction Sensor for their measurement purposes. This sensor is a low cost, general purpose instrument for general survey of wind speed and direction.

2. The FAA Vertical Flight Program Office (Washington, D.C.) tasked the NAVAIRWARCENACDIV Patuxent River ASD, via reference 1, to evaluate the Qualimetrics, Inc. model 2132 wind sensor in comparison with the TSI, Inc. model 204D ion beam deflection wind sensor. Two model 2132 wind sensors and technical liaison support from Mr. Sam Ferguson of EMA Rotorcraft/Aerodynamic Analysis were provided to NAVAIRWARCENACDIV Patuxent River ASD by Systems Control Technology, Inc. under contract to the Vertical Flight Program Office.

PURPOSE

3. This project's purpose was to assess and document the model 2132 sensor's ability to measure a rotorwash flow field as compared to the TSI model 204D ion beam deflection sensor, concentrating on the sensor's ability to capture dynamic characteristics of a helicopter rotorwash flow field.

DESCRIPTION OF TEST ARTICLES

4. The sensors being evaluated represent several technologies/techniques in measuring wind velocity and direction. The Qualimetrics, Inc. model 2132 wind sensor, illustrated in figure 1, is a low cost, cup and vane instrument designed to measure general wind conditions when precision measurements are not required. Wind speed measurements are accomplished by using a three cup anemometer attached to a rotating magnet. The magnet produces an alternating current output that is calibrated to give an AC voltage proportional to the wind speed over a range of 0 to 87 kt. Wind direction is measured by a rotating vane on a counter-weighted shaft. The shaft is connected to a potentiometer that gives an output voltage proportional to the wind direction when a DC excitation voltage is applied. For the purposes of this test, the directional vane was removed since the only data of interest was the wind's magnitude. Removal of the directional vane was believed to have no effect on the sensor's capability to measure wind magnitude and allowed better sensor integration in the wind tunnel test section. Sensor serial number 6397 was used during these tests. A more detailed description of this sensor can be obtained from reference 2.

5. The TSI, Inc. model 204D ion beam wind sensor, shown in figure 2, is considered by NAVAIRWARCENACDIV Patuxent River to be one of the best two axis instruments for accurately measuring rotorwash velocity and direction. The ion beam technology wind sensor has been used extensively over the past 16 years during assessments of the U.S. Army Heavy Lift Helicopter Rotor System, CL-84 Tilt-Wing Vertical and Short Takeoff and Landing Aircraft, CH-53E Helicopter, XV-15 Tilt Rotor Research Aircraft, and the MV-22 Tilt Rotor Aircraft, references 3, 4, 5, 6, and 7. This instrument is considered the baseline for comparison during this evaluation. It functions on the principle of projecting a beam of ionized molecules across an air gap in a direction perpendicular to the wind's motion. The ionized molecules are collected after transiting the air gap and after having been carried downstream from their point of injection. The molecules are collected onto a resistive two dimensional (X,Y) grid and produce a current in the grid that is detected by a differential amplifier. Signal processing

produces a DC output voltage for the X-axis and the Y-axis. The wind magnitude and direction are determined by resolving the wind components, Vx and Vy. The basic 204D sensor is designed to measure wind speeds over a range of 0 to 100 kt. An 80 mesh per inch screen was added over the sensing ports to expand this range to approximately 150 kt. All tests were conducted with the screen in place. Sensor serial number 64 was used for these tests. A more detailed description of this sensor can be obtained from reference 8.

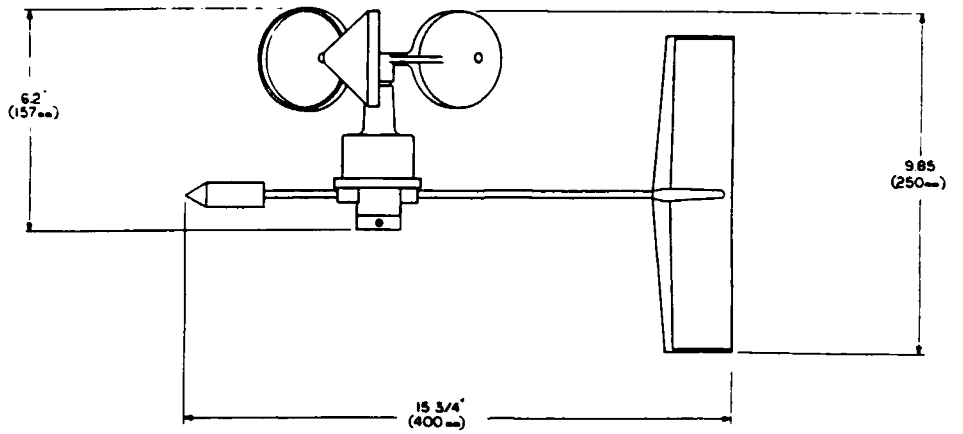

Figure 1
QUALIMETRICS, INC. MODEL 2132 COMBINATION WIND SPEED AND WIND DIRECTION SENSOR

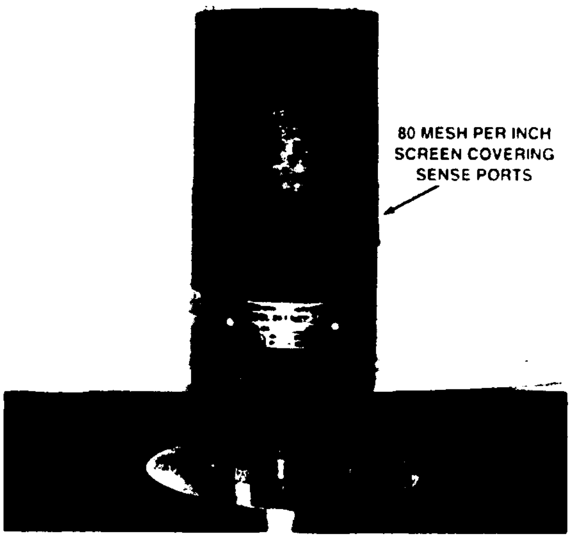

Figure 2
TSI, INC. MODEL 204D ION BEAM WIND SENSOR

SCOPE OF TESTS

6. The FAA wind sensor evaluation project was conducted from April to November 1992 and consisted of quantitative laboratory and field testing. Laboratory wind tunnel testing was conducted during July and August at the NAVAIRWARCENACDIV Patuxent River Electrical Systems Department to establish each sensor's dynamic response to a step input process at various wind tunnel velocity settings. Testing consisted of 9.5 hr of wind tunnel operation. Each sensor was subjected to three step input tests at 20 kt, 50 kt, and 80 kt velocities. Only one sensor at a time was installed in the wind tunnel due to the tunnel's test section size. The wind tunnel has a 36 in. test section diameter and is capable of 0 to 250 kt velocities. Quantitative field testing was conducted on 18 September 1992 to obtain comparative performance data in a dynamic flow field. One hour of SH-60B helicopter hover testing was conducted at aircraft gross weights ranging between 19,600 lb and 20,500 lb at 100% rotor RPM. All test data presented were obtained in ambient wind conditions of approximately 8 kt at 40 deg relative to the aircraft nose. Pressure altitude was -40 ft and ambient temperature was 85°F.

METHOD OF TESTS

7. The wind tunnel step input apparatus, presented in figures 3, 4, and 5, allowed tunnel operations at any velocity while providing a near zero velocity state at the sensor. The apparatus consisted of a base plate, a pedestal mount, which centered the sensors in the test section, a manually operated 7 in. tall by 8 in. diameter sleeve, which acted as a sensor cover when in the up position, and a trigger lever mounted external to the tunnel's test section. The sleeve was spring loaded such that, when the trigger lever was moved, the sleeve was forcefully driven downward exposing the sensor to the ambient tunnel wind velocity. The elapsed time for the sleeve to descend exposing the model 204D sensor's sensing ports was calculated to be approximately 6 msec, which was faster than the model 204D sensor's response. The model 2132 sensor was mechanically restrained inside the sleeve until the anemometer cups were fully exposed to free-stream velocity, ensuring the sensor's output was zero velocity at all wind tunnel speed settings prior to beginning the step input test. Approximately 5 sec of data were recorded for each trial. Data recording was started just prior to trigger lever activation to ensure the entire sensor response to the step input process was captured.

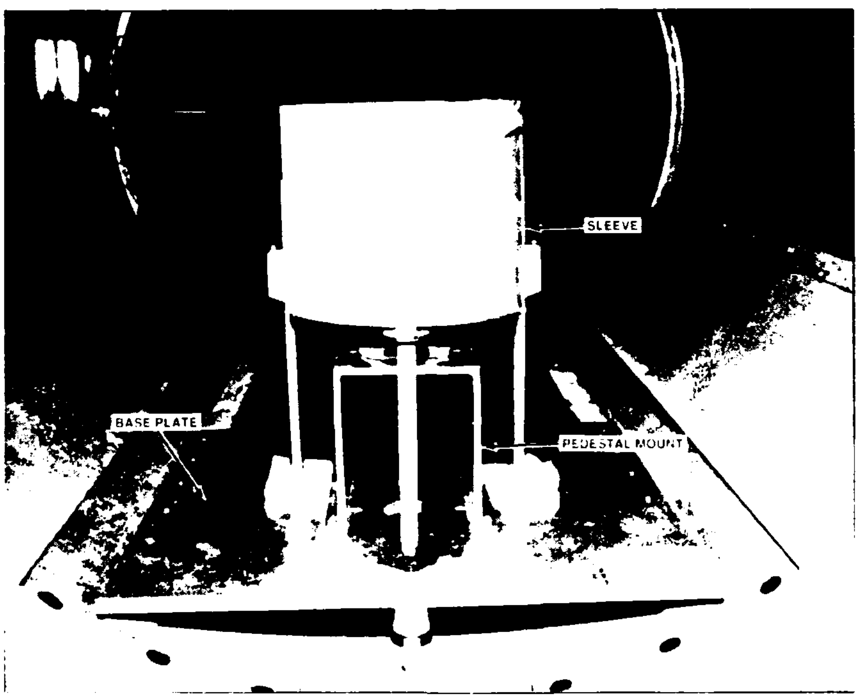

Figure 3
STEP INPUT TEST APPARATUS WITH SLEEVE RAISED, SENSOR SHIELDED FROM FLOW

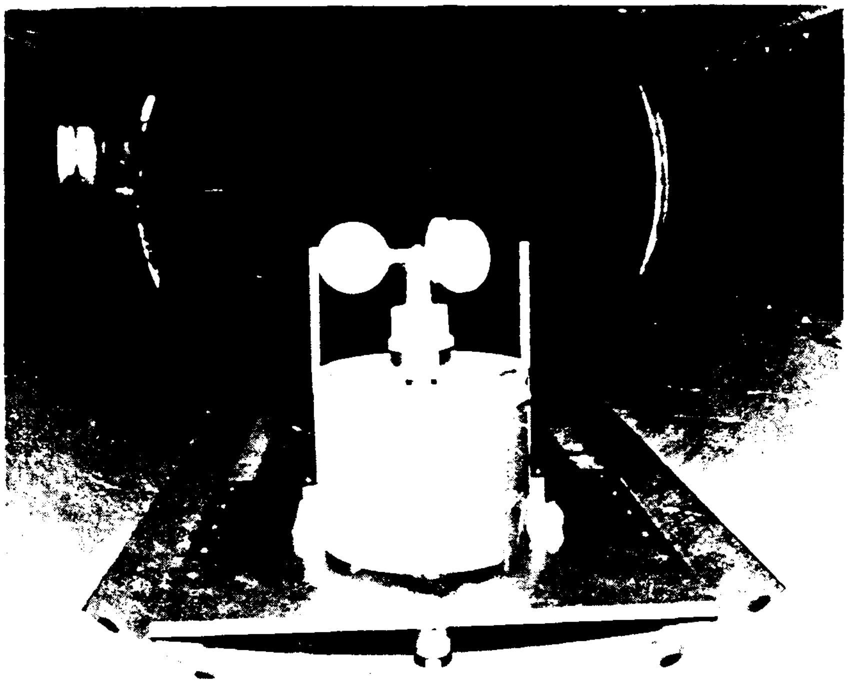

Figure 4
STEP INPUT TEST APPARATUS WITH SLEEVE LOWERED, SENSOR EXPOSED TO FLOW

Figure 5
STEP INPUT TEST APPARATUS TRIGGER LEVER IN THE CLOSED POSITION

8. Laboratory data were recorded using Labtech Notebook V and an in-house developed IBM personal computer based data acquisition software program for the model 204D and model 2132 sensors, respectively. The model 2132 sensor was sampled at 4000 Hz to accurately capture the AC output signal. All sensor data were digitally stored for data reduction. A 12 bit A/D data acquisition system allowed for velocity resolutions of 0.06 and 0.01 kt for the model 204D and model 2132 sensors, respectively.

9. The laboratory step input performance test data were analyzed to determine each sensor's response performance characteristics at each wind tunnel velocity setting. The data were analyzed using the process contained in reference 9 as guidance. This process established each sensors' time constant value, represented by time divided by the greek letter tau (τ) or (t/τ).

10. As illustrated in figure 6, a first order instrument will approach the step input driving function with the exponential response $Y = 1\text{-}e\text{^}(-t/\tau)$. The sensor will achieve 63.2% of the step function in one time constant (t/τ), 86.5% at 2(t/τ), 95% at 3(t/τ), and 100% at infinite (t/τ). Time constants were determined by plotting nondimensionalized velocity (V/V_{final}) versus time (t/τ) and performing an exponential curve fit on the resultant curve. The curve fit was optimized by minimizing the data file's root-mean-square error between the theoretical and experimental data. Three data files were collected and analyzed for each sensor at each wind tunnel velocity setting to justify the sensors' time constant selection and to check for data repeatability. The high and low value of each data set was discarded allowing selection of a single time constant representing each velocity setting. An indication of how well the sensor would respond in a dynamic environment was obtained by comparing each sensor's time constant for each test event.

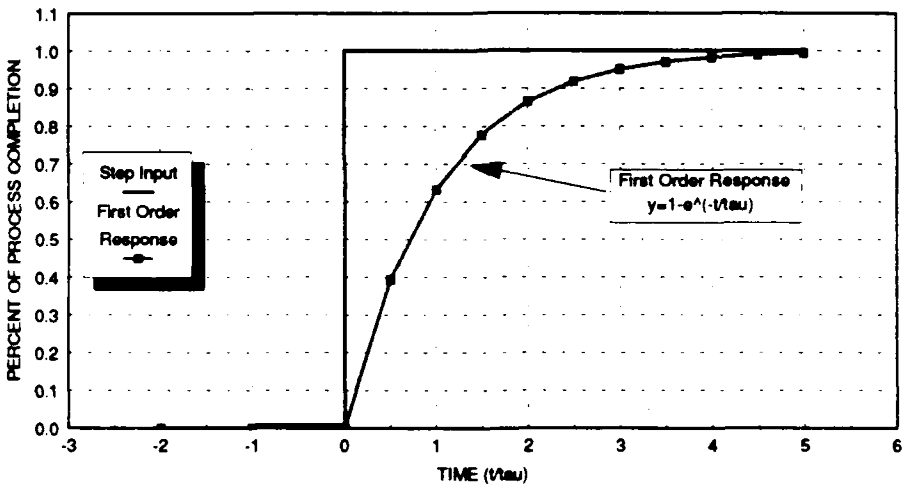

Figure 6
FIRST ORDER INSTRUMENT RESPONSE TO A STEP INPUT

11. Data to determine the model 2132 sensor's ability to measure rotorwash flow field dynamics, as compared to the ion beam sensor, were collected while the sensors were mounted in the side by side arrangement shown in figure 7. The sensors were positioned at 1.5 ft above the ground and separated laterally by approximately 2 ft to prevent sensor to sensor interference. Previous testing of other hovering aircraft indicated that the downwash flow is primarily horizontal at this 1.5 ft height for the rotor radii tested. The sensors were stimulated by an SH-60B helicopter hovering at 15 ft and 25 ft AGL at 35 ft and 70 ft distances from the sensors as measured from hover site center. The sensors were positioned directly in front of the helicopter. Table 1 lists the data collection test points. Figure 8 shows the aircraft at 15 ft AGL and 35 ft from the sensors.

Figure 7
SENSOR MOUNTING ARRANGEMENT DURING HOVER TESTS

Table 1

HOVER TEST POINT MATRIX

Event	Aircraft Hover Height (ft)[1]	Sensor Distance From Hover Site Center (ft)[2]	Remarks
1	15	35	1.3 rotor radii
2	25	35	
3	15	70	2.6 rotor radii
4	25	70	

1. Hover height as measured by the aircraft radar altimeter.

2. Hover site center is defined as the point on the ground that is directly beneath the center of the main rotor during hover.

Figure 8
SH-60B HOVERING 15 FT AGL AT 35 FT FROM THE WIND SENSORS

12. Field test data were recorded on a Gould 6500 and a Nagra T FM multi-channel tape recorder for the model 204D and model 2132 sensors, respectively. The model 204D data were recorded in digital pulse code modulated format. Each recorder had an analog voice channel to annotate test event data record starts and allow for correlating time histories to support dynamic data comparison. The FM analog data tape was converted to digital data files for data reduction.

13. Field test data were reduced via an in-house developed computer program, which provided tabulated velocity magnitude versus time data files. The magnitudes of the velocity data were analyzed by examining a 20 sec time interval from each sensor. Average velocities were computed for each 20 sec period. The oscillatory or pulsating nature of flow fields cause large variation in the velocity magnitudes. These large variations or pulses are represented throughout this report as peak and trough values and are the basis for comparison of the model 2132 sensor's ability to capture the dynamics of a downwash flow field.

RESULTS AND DISCUSSION

14. Past experience with measuring and analyzing helicopter rotorwash effects on personnel has revealed the importance of accurately capturing rapid oscillations in the flow field. These dynamic flow field characteristics directly relate to a person's or a piece of equipment's stability when enveloped in a flow field. Use of a sensor without sufficient dynamic response may result in calculated dynamics and forces that are much different than those actually present.

LABORATORY TESTS

15. The step input performance characteristics of the model 204D and the model 2132 wind sensors were analyzed to compare their basic dynamic response characteristics. Figures 1 through 6 of appendix A contain plots of nondimensionalized velocity versus time and were used to determine the sensors' time constant values. Calculated model 204D and model 2132 time constant values are summarized in table 2.

Table 2

CALCULATED MODEL 204D AND MODEL 2132 TIME CONSTANT VALUES

Wind Tunnel Velocity (kt)	Test Run	Time Constants (sec)	
		Model 204D	Model 2132
20	1	0.0251*	0.479
	2	0.0247	0.480*
	3	0.0289	0.489
50	1	0.0294	0.197
	2	0.0309*	0.219*
	3	0.0338	0.228
80	1	0.0275*	0.129
	2	0.0273	0.121
	3	0.0293	0.124*

* Denotes value selected to represent that particular wind sensor at that particular wind tunnel velocity.

As a general rule, minimizing the value of a sensor's time constant will maximize its ability to faithfully make dynamic measurements. Data analysis indicates the model 2132's time constant values were significantly higher than those of the model 204D and varied relative to wind tunnel velocity setting. While the model 204D's time constant values remained relatively stable, the model 2132's time constant values decreased as wind tunnel velocity increased and remained significantly higher than the model 204D sensor's. Figure 9 illustrates a first order instrument's ability to accurately measure a dynamic signal as a function of its time constant. The figure indicates that the model 204D sensor should provide accurate measurements (within 5%) for frequencies up to 10 Hz. At best, the model 2132 will be accurate (within 5%) for frequencies up to 3 Hz at higher wind velocities (i.e., 80 kt) and 1.5 Hz at lower velocities (i.e., 20 kt). The model 2132 sensors' significantly higher time constant values, even at higher free-stream velocities, are evidence that its ability to accurately capture oscillations in a dynamic flow field is significantly less than the model 204D sensor.

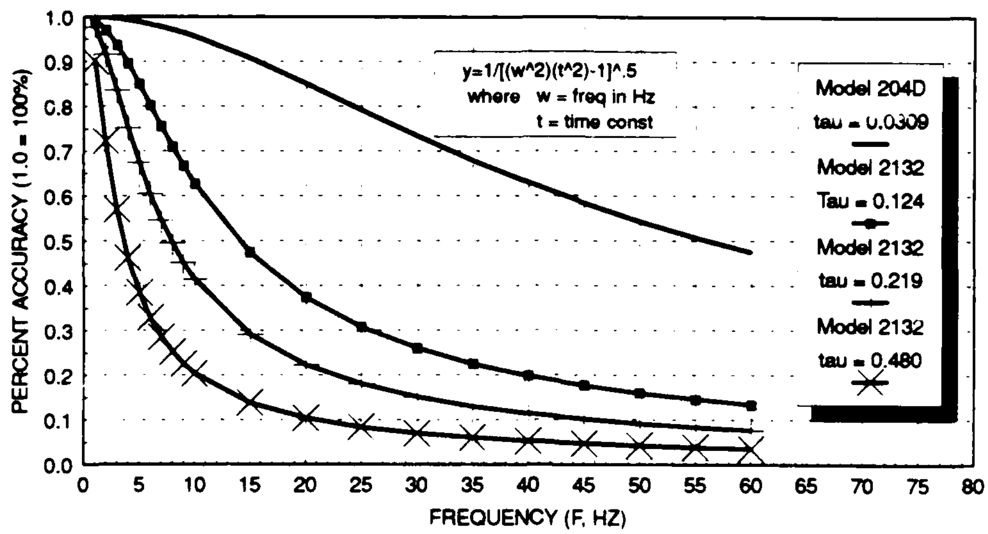

Figure 9
MODEL 204D AND MODEL 2132 WIND SENSOR FREQUENCY MEASUREMENT ACCURACY

DYNAMIC PERFORMANCE TESTS

FLOW FIELD DYNAMICS

16. The model 2132 sensor did detect periodic or pulsating velocities in the flow field but failed to capture significant oscillations as compared to the model 204D sensor. Figure 10 is a time series plot that illustrates typical velocity waveforms of the helicopter generated flow field as measured by each sensor. Frequency content of both sensor outputs was determined using power spectral density analysis and indicated the model 2132 sensor was unable to detect all major flow field energy at low frequencies. The low frequency energy is the most significant part of the spectrum relative to determining stability or instability of human or objects enveloped in a flow field (references 5 and 6). Figure 11 is a typical power spectrum and represents the data collected during the second field test event (25 ft AGL hover at 35 ft from sensors). This figure's data indicate that the model 2132 sensor failed to capture significant pulses at frequencies above 1 Hz and captured only 30% of the maximum amplitude of the pulses below 1 Hz. Figures 7 through 10 of appendix A contain both sensors' power spectral density data for all field test events. Comparative analysis of all field test event data indicate the model 2132 sensor only detected frequencies below 1.5 Hz and only captured an average of 46% of the model 204D sensor's maximum amplitude pulse values that were below 1.5 Hz. The model 2132 sensor's inability to capture the maximum pulse amplitudes is evidence of the sensor's limited capability to capture peak and trough velocity magnitude variations in a flow field. The model 2132 sensor is not recommended for helicopter downwash velocity data collection due to its limited capability to fully capture significant flow field oscillations thus limiting the user's ability to accurately analyze the flow field's frequency content.

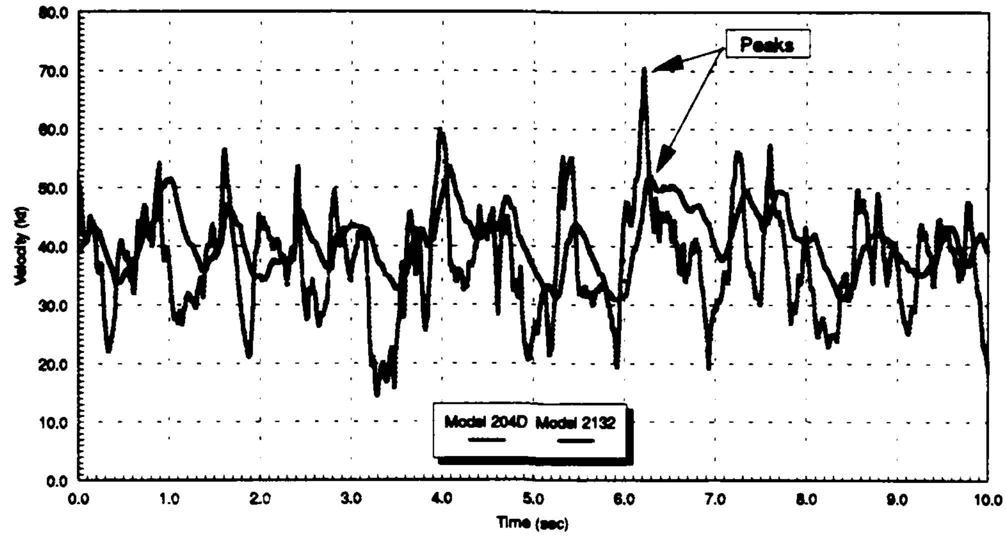

Figure 10
TIME SERIES OF WIND VELOCITY MAGNITUDE MEASURED AS THE AIRCRAFT WAS HOVERING 15 FT AGL AT 35 FT FROM THE SENSORS

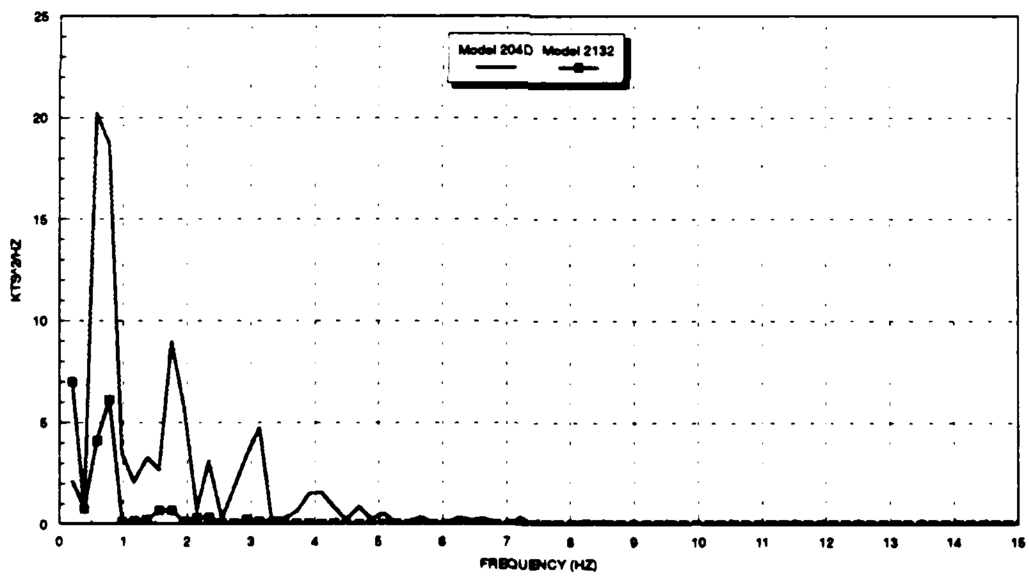

Figure 11
POWER SPECTRAL DENSITY OF DATA COLLECTED WITH THE AIRCRAFT HOVERING 25 FT AGL AT 35 FT FROM THE SENSORS

VELOCITY COMPARISONS

17. The model 2132 sensor failed to accurately measure the peak and trough flow field velocities as compared to the model 204D sensor. Figures 11 through 14 of appendix A contain each sensors' velocity magnitude plotted versus time. The model 2132 sensor waveform appeared to follow the model 204D sensor's general velocity waveform pattern in the first two events with minor lags between oscillations. It was difficult, though, to make any correlations between the sensors' waveform patterns in the last two field test events; therefore, data analysis concentrated on the first two field events. It is apparent, after viewing the plotted velocity versus time data, that the model 2132 sensor did not accurately capture the major peak or trough velocities detected by the model 204D sensor. In order to quantify and compare the model 2132 sensor's ability to capture flow field velocity oscillations, the model 2132 sensor peak velocities were chosen by noting the peak velocity magnitude that occurred just after a model 204D peak output was noted. For example, referring to figure 10, the maximum 204D sensor peak value was 70.5 kt and occurred at approximately 6.2 sec. The corresponding 2132 sensor peak value was determined to be 52.3 kt and occurred at approximately 6.26 sec. This translates to the model 2132 sensor detecting only 74% of the model 204D sensor's measured peak in this case. Table 3 contains the peak, minimum (trough), and average velocities recorded for each sensor during the first two field test events.

Table 3

MODEL 204D AND MODEL 2132 SENSOR VELOCITY SUMMARY

Velocity	Event 1		Event 2	
	204D	2132	204D	2132
Average (kt)	37.2	40.9	30.6	33.8
Peak (kt)	70.5	52.1	64.4	48.1
Minimum (kt)	14.3	30.8	6.9	23.1

18. The model 2132 sensor's average and minimum velocities for each test event were significantly higher than the model 204D sensor's. Higher average velocities can be attributed to the sensor's inability to rapidly detect diminishing velocity pulses. This is additional evidence that the model 2132 sensor is slower to respond to rapid changes in a dynamic flow field. This is evident in figures 11 and 12 of appendix A which clearly illustrate that the sensor failed to detect the troughs (minimum velocities) as measured by the model 204D sensor. The combination of many factors, such as internal friction, vibration, mass, kinetic energy, and aerodynamics, contribute to the model 2132 sensor's ability to accelerate and decelerate in a dynamic flow field. The overall sensor design promotes more rapid acceleration than deceleration. The higher average and minimum measurements occurred because of the aerodynamic design of the model 2132 sensor's rotating head. While each cup is identical in shape and size, their arrangement about the center of rotation and relative orientation to oncoming wind affects its ability to respond to rapid changes in free-stream velocity. As a wind pulse initially contacts the anemometer, each cup's relative position to oncoming wind allows for maximum continuous acceleration via high drag force (front of cup design) while simultaneously minimizing the decelerative effects of aerodynamic drag (rear of cup design). The rear of the cups' design coupled with the rotating mass reduces the sensor's capability to slow down as a velocity pulse decreases. Figure 12 illustrates the inability of the model 2132 sensor to respond to rapid decelerations. The sensor was exposed to a constant 22.5 kt velocity, allowed to stabilize, and then rapidly removed to a zero velocity ambient environment. The sensor required in excess of 15 sec to reach zero velocity. This greater than 15 sec deceleration time from approximately 20 kt is significantly longer than the

2.4 sec acceleration noted during the step input response tests. This will result in detected minimum velocity being higher than what really exists, increasing the calculated average. The model 2132 sensor is not recommended for helicopter downwash velocity data collection due to its limited capability to capture peak and trough velocity variations as well as its inability to accurately represent average flow field velocities, thus limiting the user's ability to accurately analyze the flow field's velocity content.

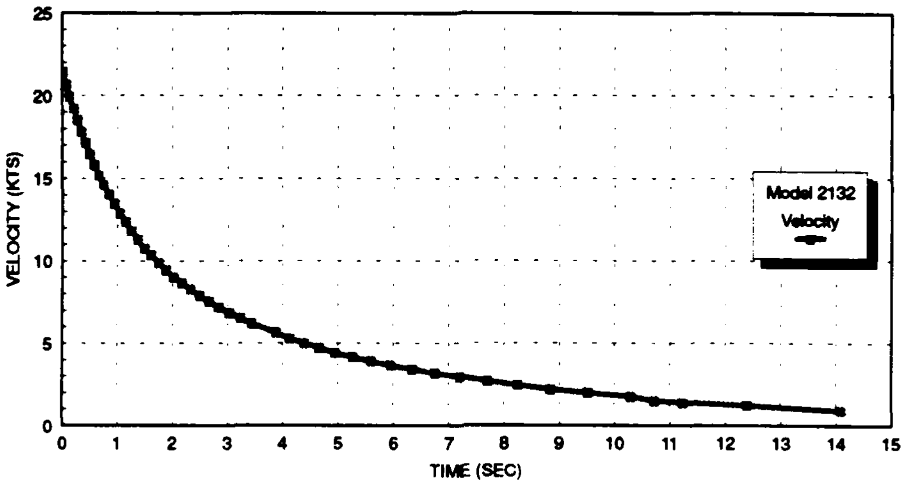

Figure 12
TIME HISTORY OF MODEL 2132 WIND SENSOR VELOCITY DECAY UPON REMOVAL OF STIMULUS

CONCLUSIONS

GENERAL

19. Compared to the TSI, Inc. model 204D wind sensor, the Qualimetrics, Inc. model 2132 wind sensor failed to accurately measure a rotorwash flow field in terms of frequency, amplitude, frequency content, and velocity magnitude.

SPECIFIC

20. The model 2132 sensor's time constant values were significantly higher than those of the model 204D sensor and varied relative to wind tunnel velocity setting (paragraph 15).

21. The model 2132 sensor did detect periodic or pulsating velocities in the flow field but failed to capture significant oscillations as compared to the model 204D sensor (paragraph 16).

22. Comparative analysis of all field test event data indicate the model 2132 sensor only detected frequencies below 1.5 Hz and only captured an average of 46% of the model 204D sensor's maximum amplitude pulse values that were below 1.5 Hz (paragraph 16).

23. The model 2132 sensor's inability to capture the maximum pulse amplitudes is evidence of the sensor's limited capability to capture peak and trough velocity magnitude variations in a flow field (paragraph 16).

24. The model 2132 sensor failed to accurately measure the peak and trough flow field velocities as compared to the model 204D sensor (paragraph 17).

25. The model 2132 sensor's average and minimum velocities for each test event were significantly higher than the model 204D sensor's and can be attributed to the sensor's inability to rapidly detect diminishing velocity pulses (paragraph 18).

RECOMMENDATIONS

26. The model 2132 sensor is not recommended for helicopter downwash velocity data collection due to its limited capability to fully capture significant flow field oscillations thus limiting the user's ability to accurately analyze the flow field's frequency content (paragraph 16).

27. The model 2132 sensor is not recommended for helicopter downwash velocity data collection due to its limited capability to capture peak and trough velocity variations as well as its inability to accurately represent average flow field velocities, thus limiting the user's ability to accurately analyze the flow field's velocity content (paragraph 18).

REFERENCES

1. Interagency Agreeme :t No. DTFA01-92-Y-02017 Between the Federal Aviation Administration and the Naval Air Warfare Center Aircraft Division Systems Engineering Test Directorate of 10 Apr 1992.

2. Manual for the Combination Wind Speed and Wind Direction Sensor Model 2132 of Nov 1985.

3. NAVAIRTESTCEN Technical Report SY-17R-76, Downwash Evaluation Under the U.S. Army Heavy Lift Helicopter Rotor, Final Report, of 16 Mar 1976.

4. NAVAIRTESTCEN Technical Report SY-52R-76, CL-84 Tilt-Wing Vertical and Short Takeoff and Landing Downwash Evaluation, Final Report, of 9 Apr 1976.

5. NAVAIRTESTCEN Technical Report SY-89R-78, CH-53E Helicopter Downwash Evaluation, Final Report, of 1 Aug 1978.

6. NAVAIRTESTCEN Technical Report SY-14R-83, Technical Evaluation of the Rotor Downwash Flow Field of the XV-15 Tilt Rotor Research Aircraft, Final Report, of 28 Jul 1983.

7. NAVAIRTESTCEN Technical Report RW-71R-90, Navy Developmental Test (DT-IIA) of the MV-22 Aircraft, Contributory Test Report on Rotor Downwash, Appendix Q, of 15 Feb 1991.

8. Operating and Maintenance Manual for the Model 204D Wind Sensor, Undated.

9. Doebelin, E. O., "Measurement Systems: Application and Design", McGraw-Hill Inc., 1975.

APPENDIX A: FIGURES

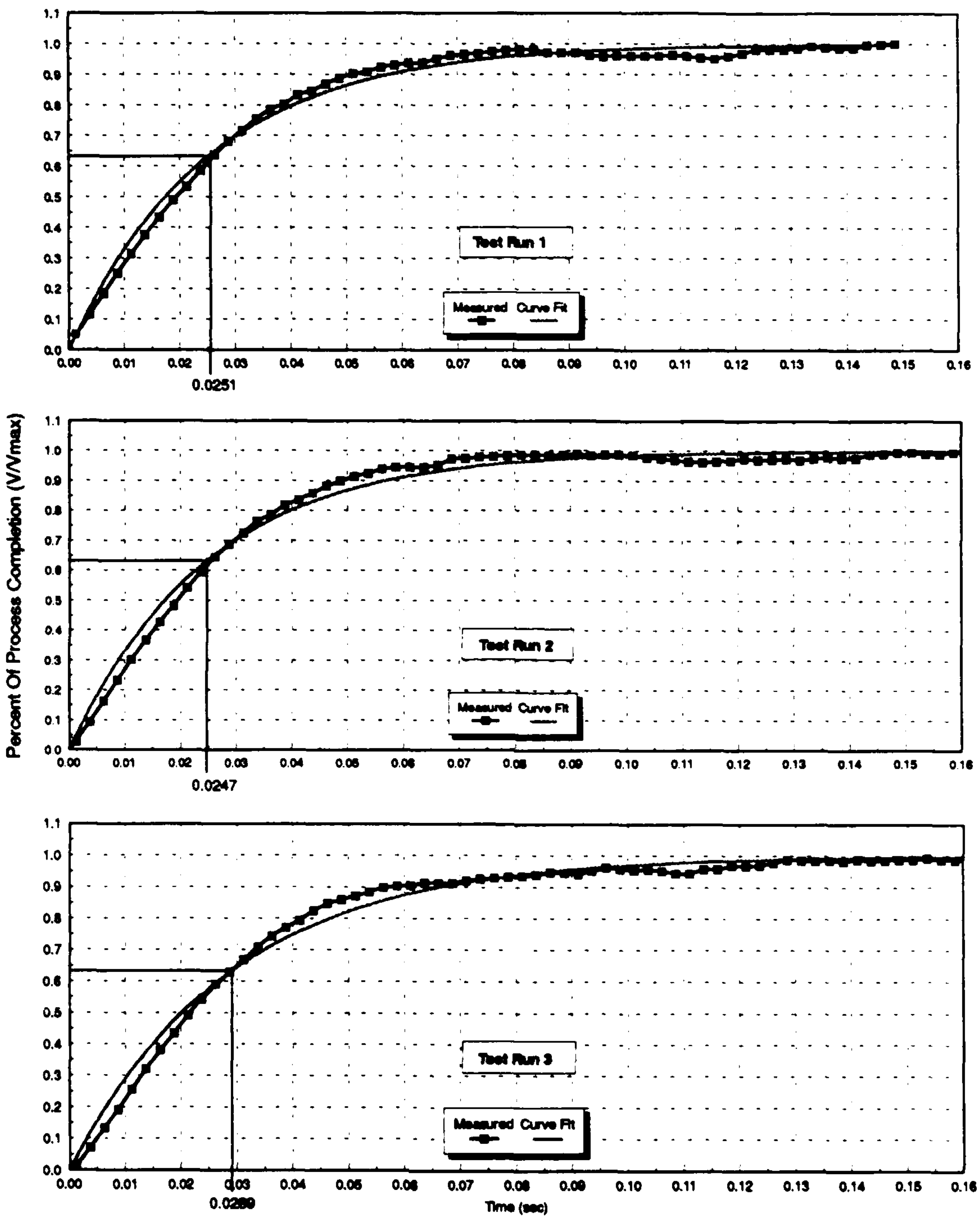

Figure 1
MODEL 204D STEP INPUT TEST RESULTS FOR A WIND TUNNEL VELOCITY OF 20 KTS

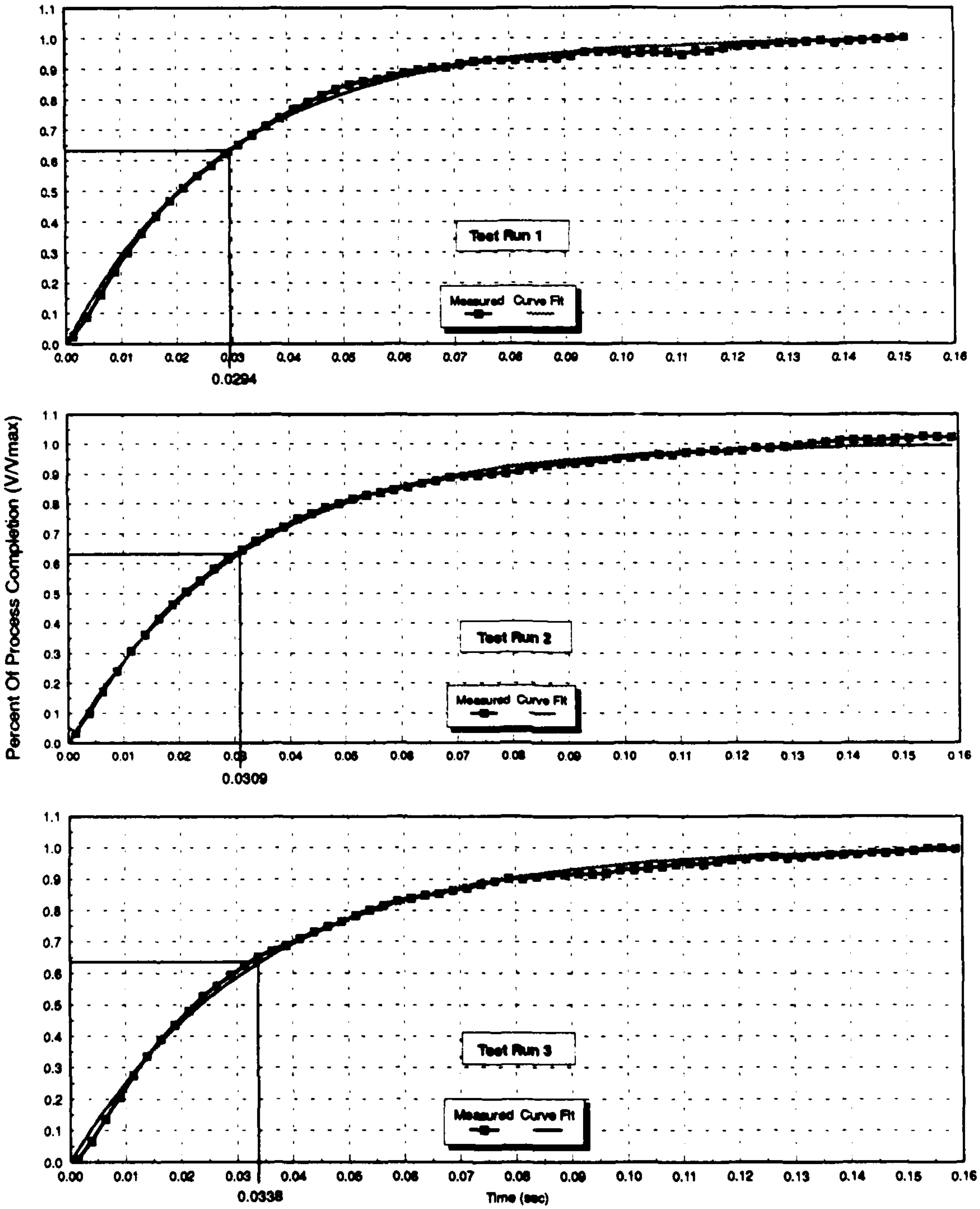

Figure 2
MODEL 204D STEP INPUT TEST RESULTS FOR A WIND TUNNEL VELOCITY OF 50 KTS

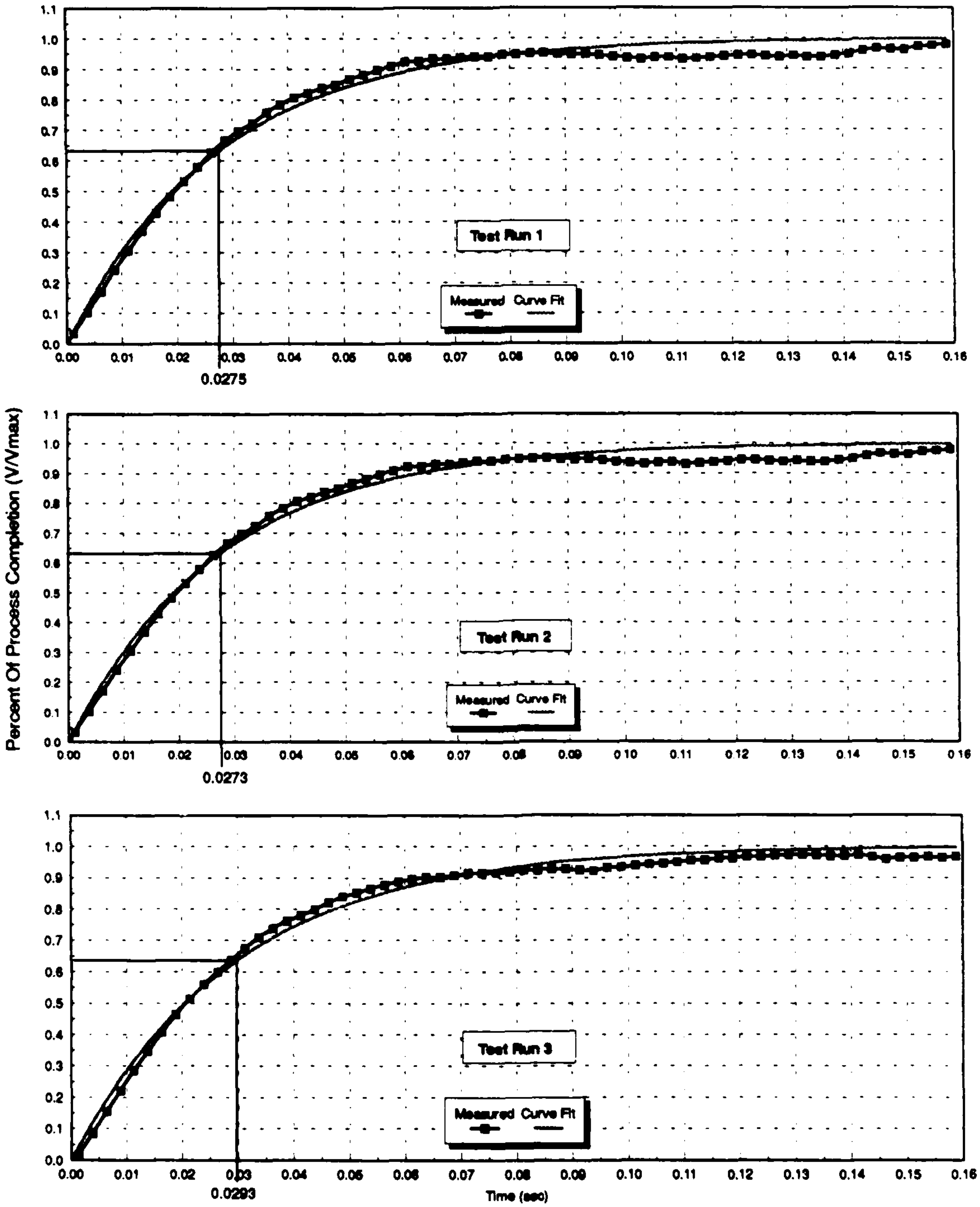

Figure 3
MODEL 204D STEP INPUT TEST RESULTS FOR A WIND TUNNEL VELOCITY OF 80 KTS

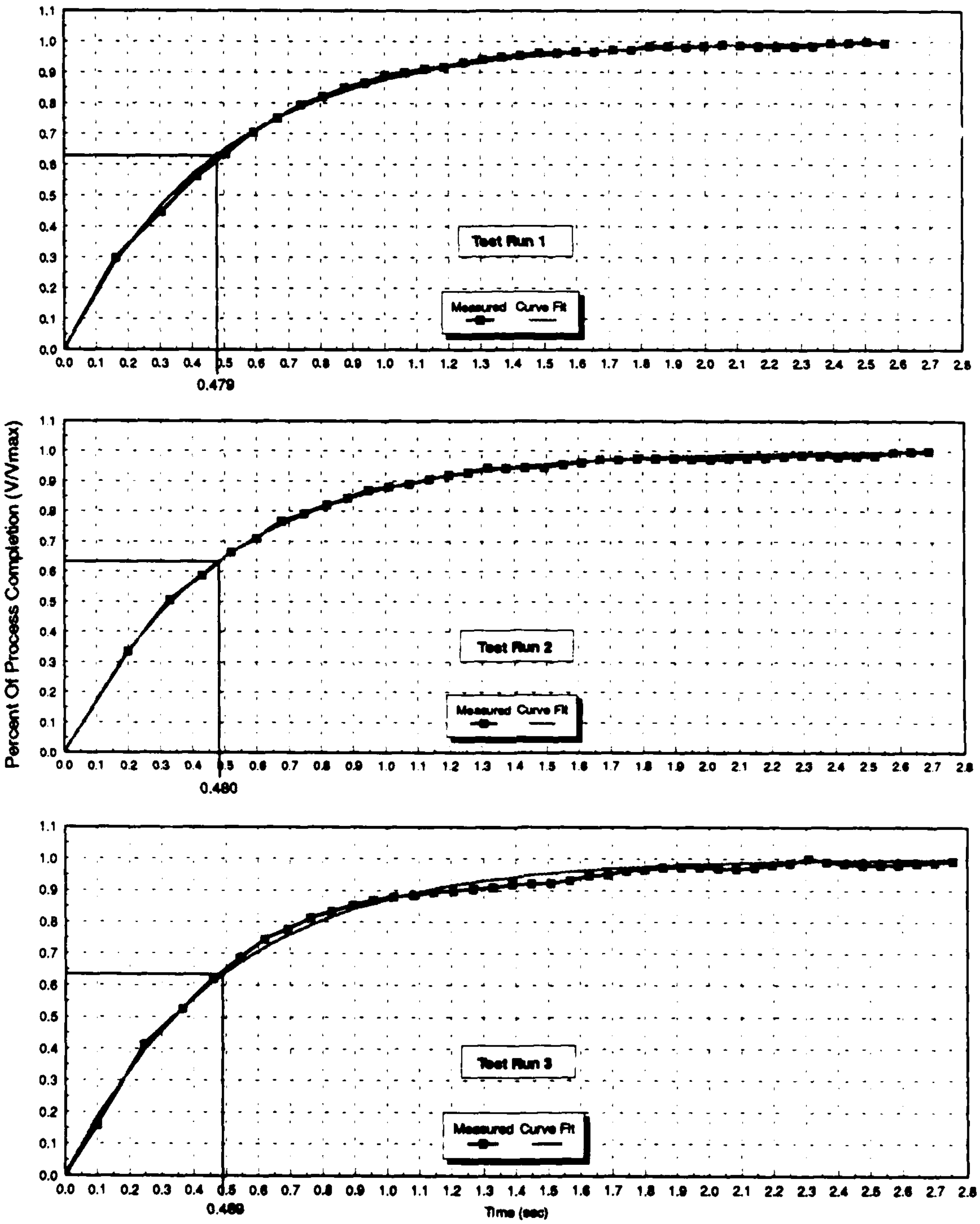

Figure 4
MODEL 2132 STEP INPUT TEST RESULTS FOR A WIND TUNNEL VELOCITY OF 20 KTS

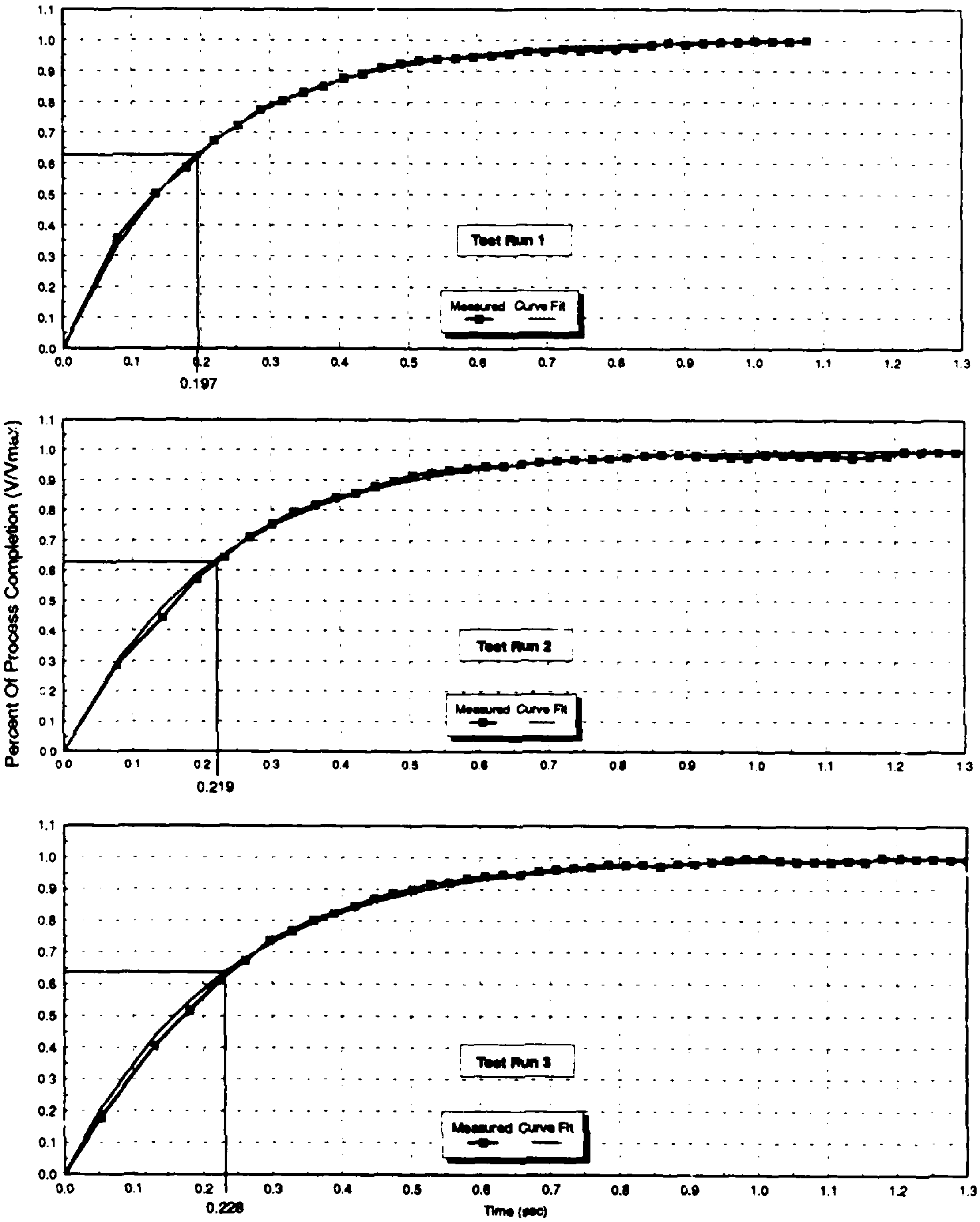

Figure 5
MODEL 2132 STEP INPUT TEST RESULTS FOR A WIND TUNNEL VELOCITY OF 50 KTS

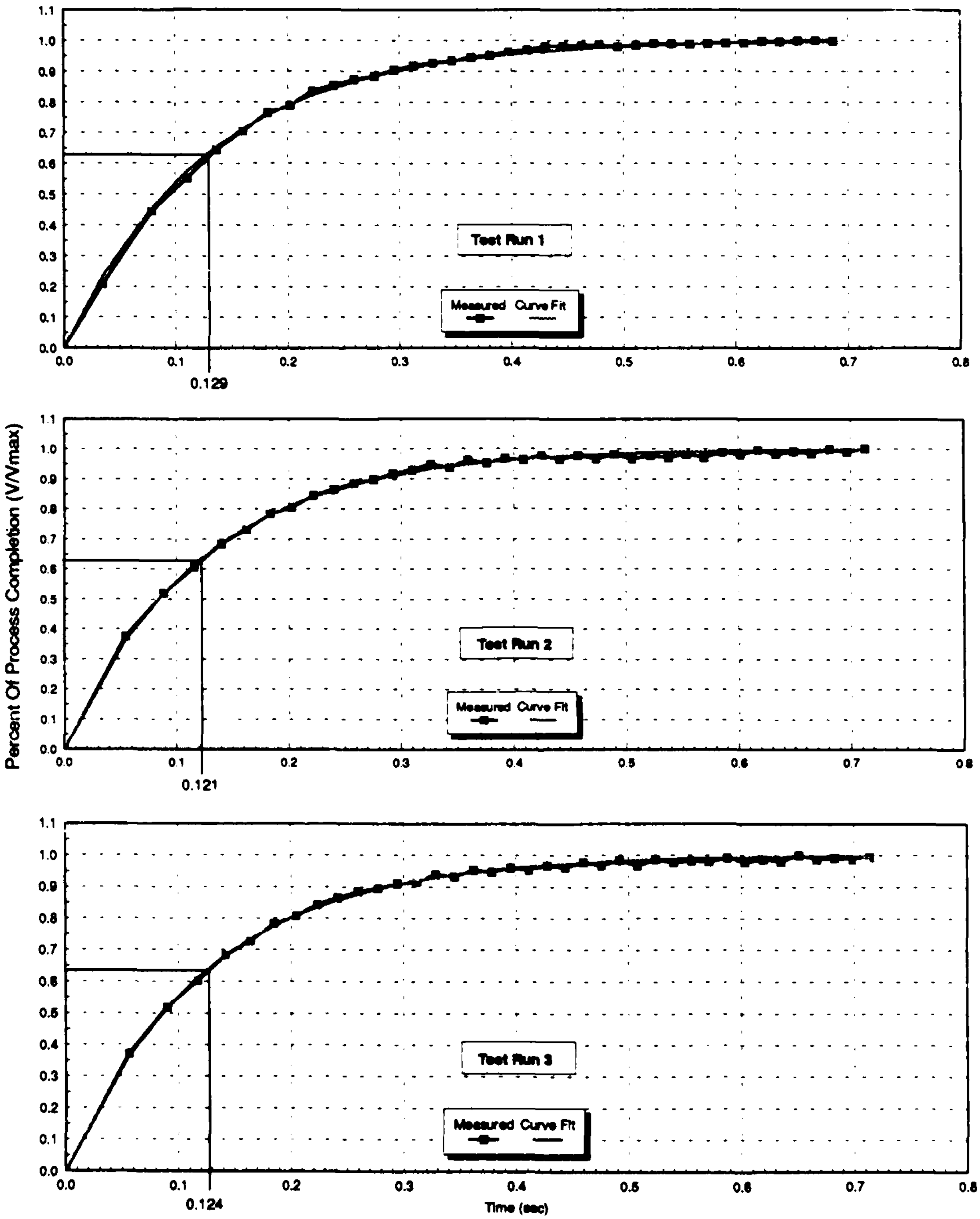

Figure 6
MODEL 2132 STEP INPUT TEST RESULTS FOR A WIND TUNNEL VELOCITY OF 80 KTS

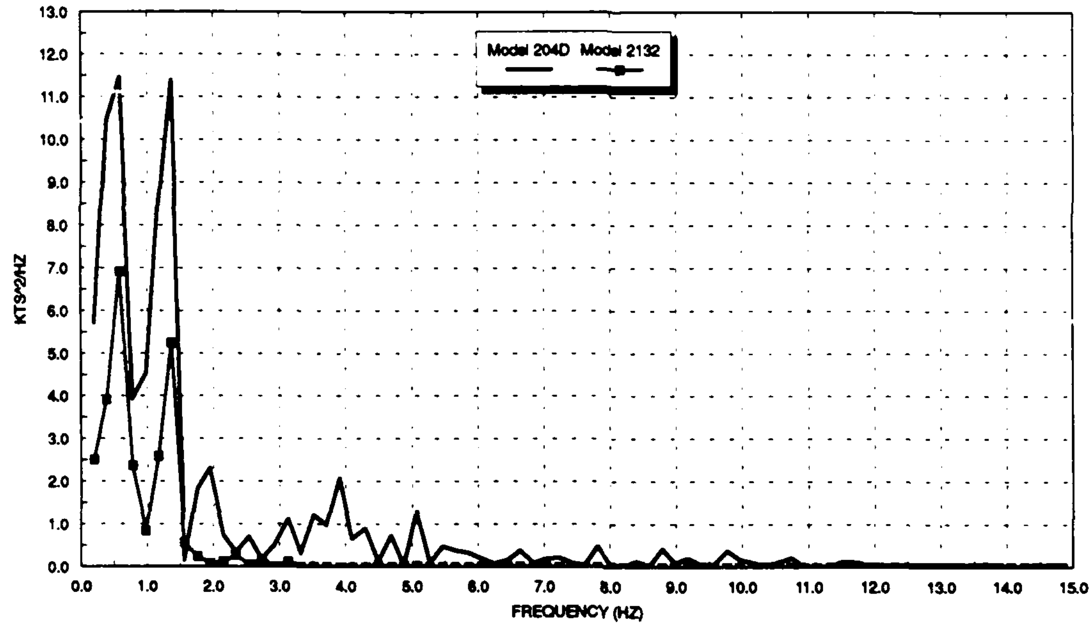

Figure 7
POWER SPECTRAL DENSITY OF DATA OBTAINED WHILE THE AIRCRAFT WAS HOVERING 15 FT AGL AT 35 FT FROM THE SENSORS

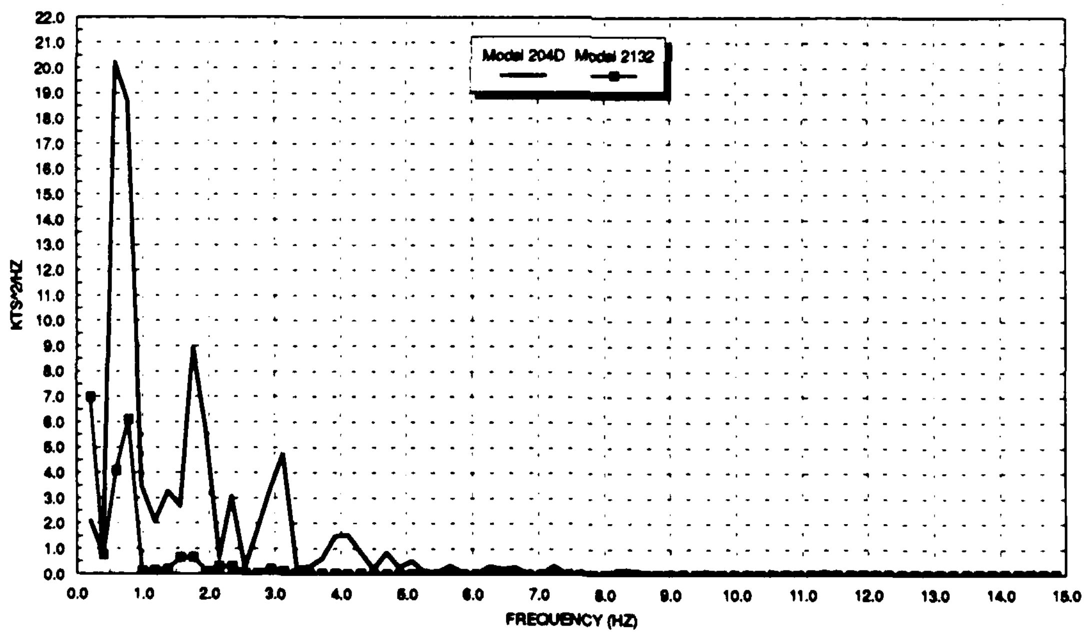

Figure 8
POWER SPECTRAL DENSITY OF DATA OBTAINED WHILE THE AIRCRAFT WAS HOVERING 25 FT AGL AT 35 FT FROM THE SENSORS

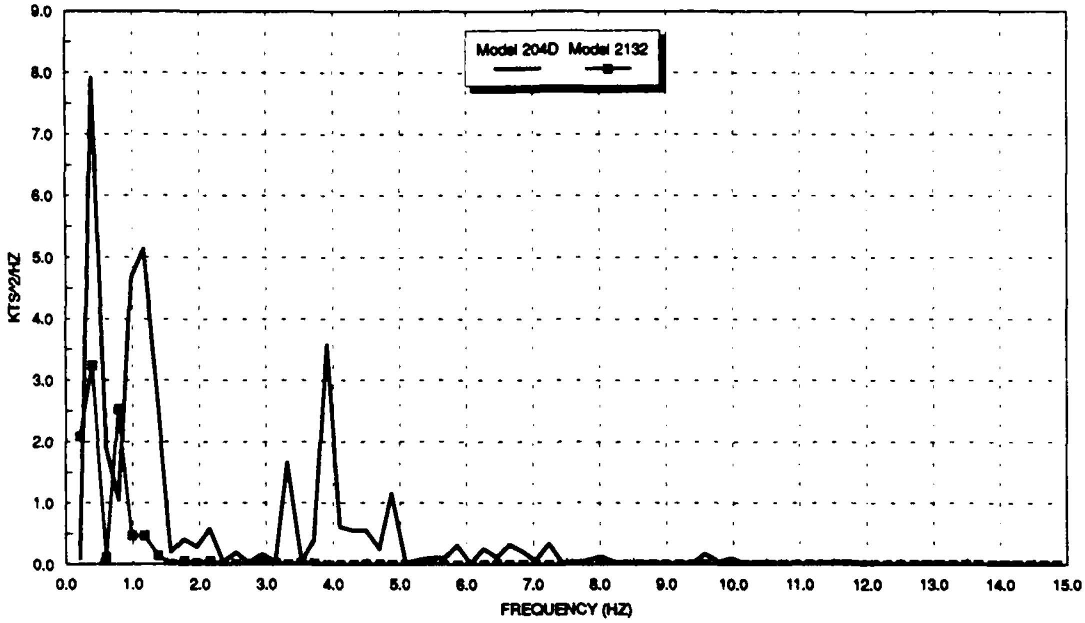

Figure 9
POWER SPECTRAL DENSITY OF DATA OBTAINED WHILE THE
AIRCRAFT WAS HOVERING 15 FT AGL AT 70 FT FROM THE SENSORS

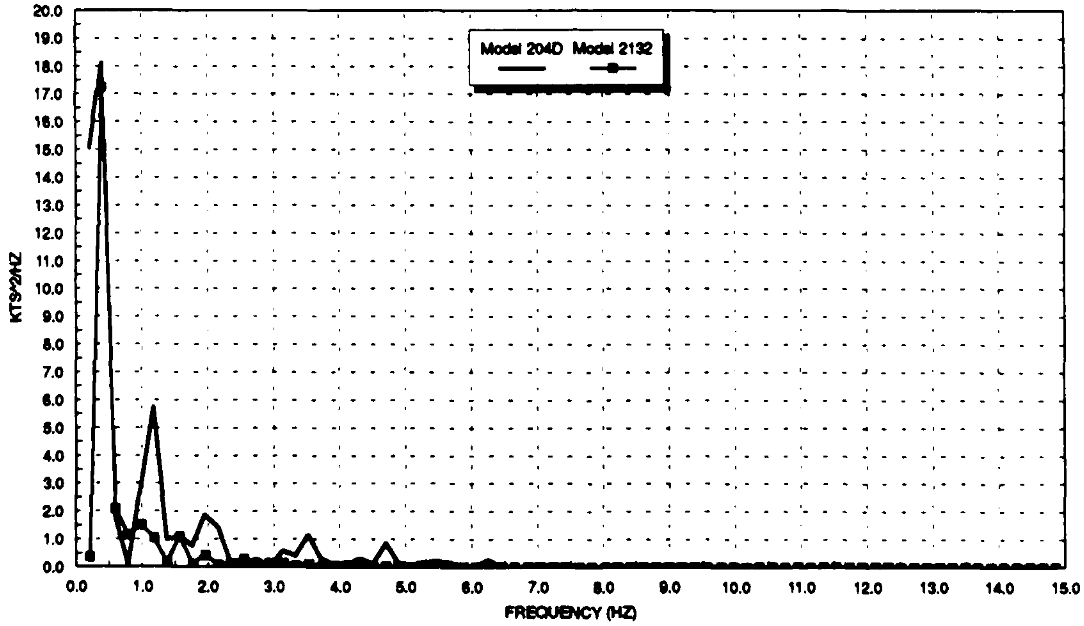

Figure 10
POWER SPECTRAL DENSITY OF DATA OBTAINED WHILE THE
AIRCRAFT WAS HOVERING 25 FT AGL AT 70 FT FROM THE SENSORS

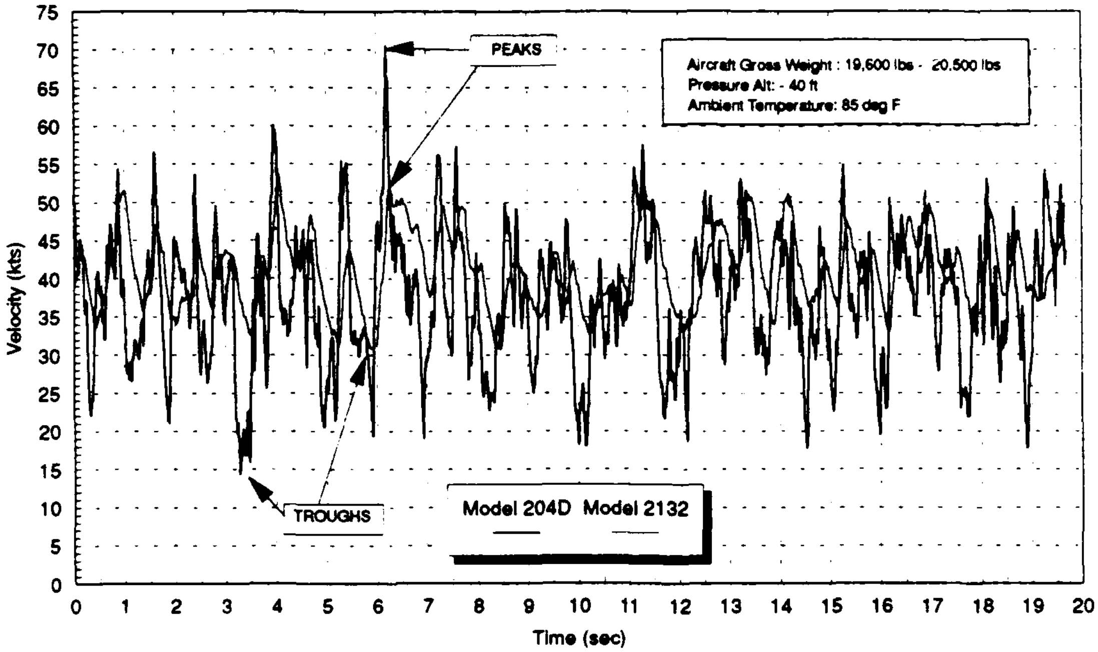

Figure 11

TIME SERIES OF WIND VELOCITY MAGNITUDE MEASURED AS THE AIRCRAFT WAS HOVERING 15 FT AGL AT 35 FT FROM THE SENSORS

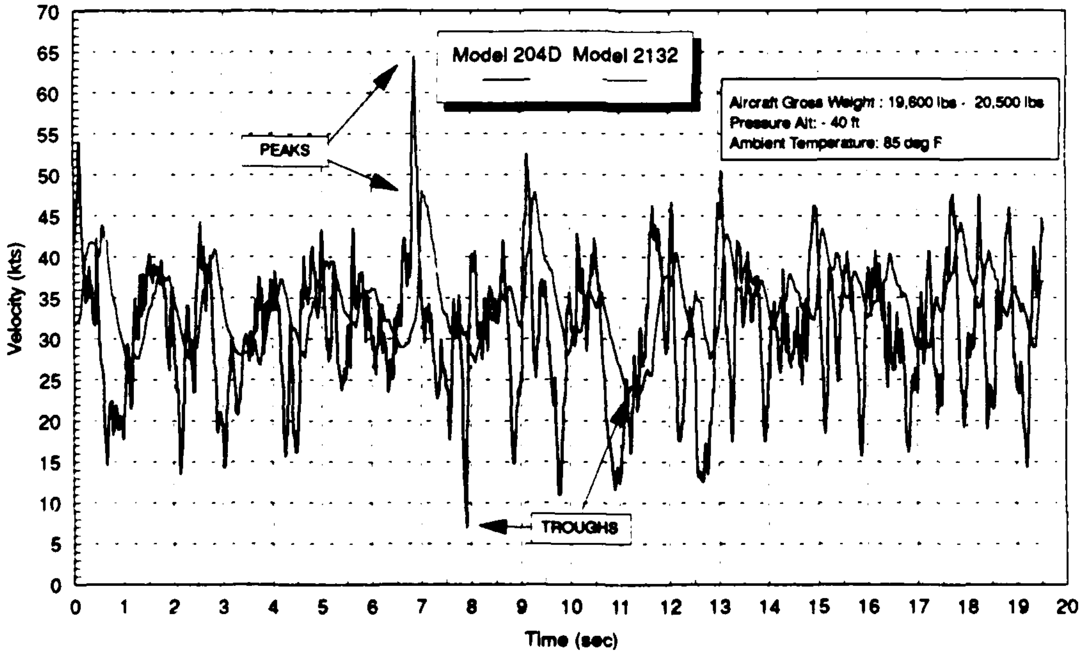

Figure 12

TIME SERIES OF WIND VELOCITY MAGNITUDE MEASURED AS THE AIRCRAFT WAS HOVERING 25 FT AGL AT 35 FT FROM THE SENSORS

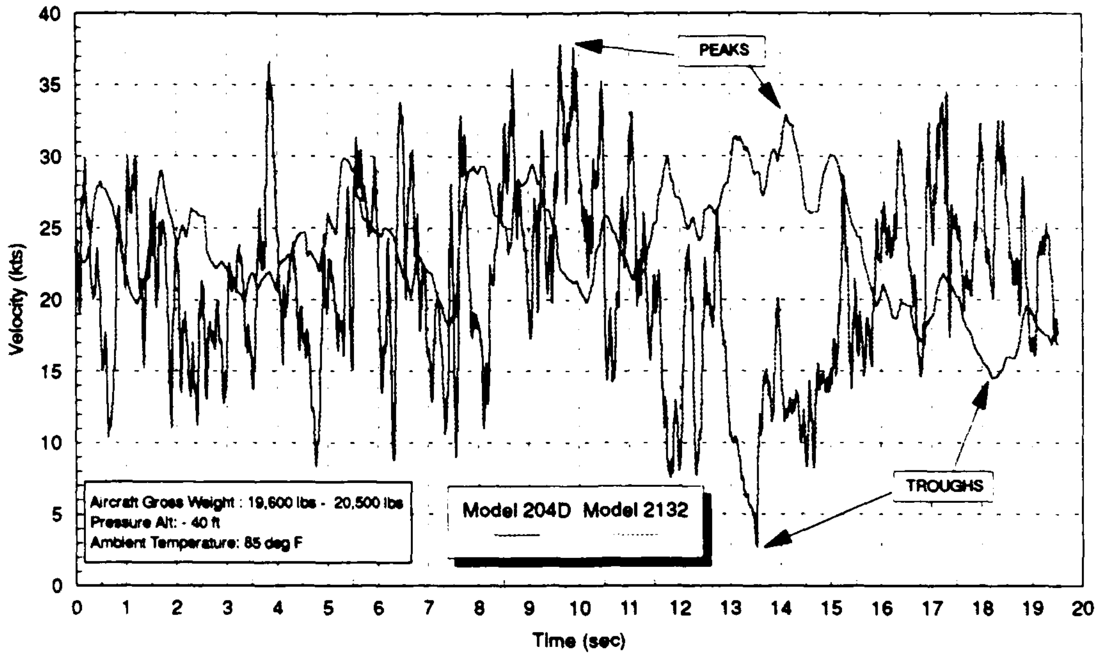

Figure 13
TIME SERIES OF WIND VELOCITY MAGNITUDE MEASURED AS THE AIRCRAFT WAS HOVERING 15 FT AGL AT 70 FT FROM THE SENSORS

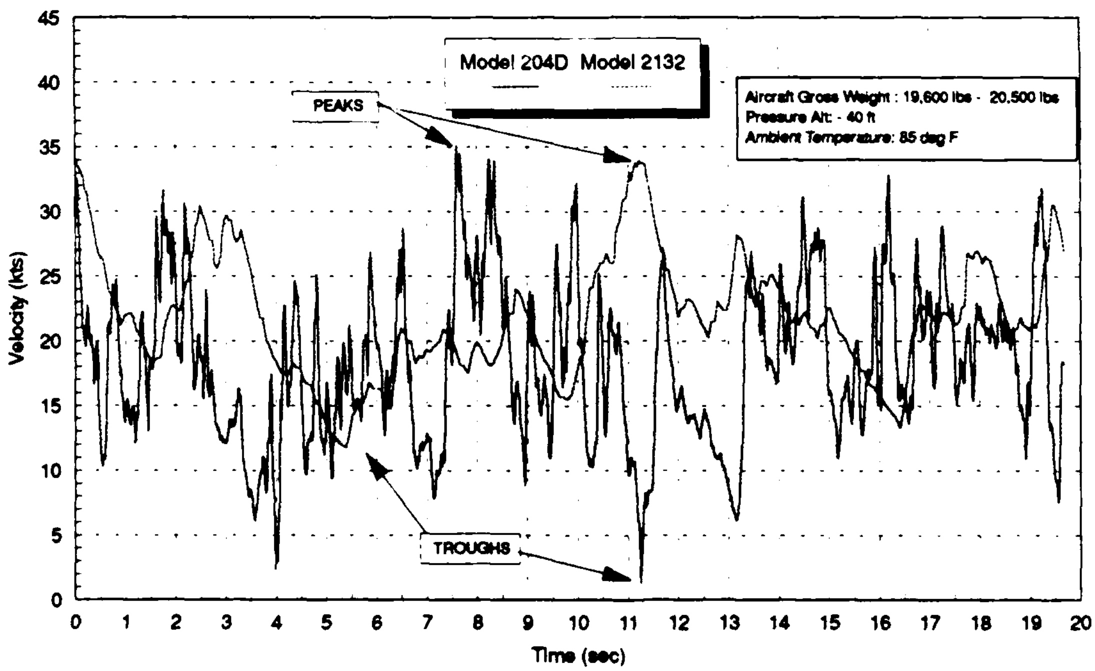

Figure 14
TIME SERIES OF WIND VELOCITY MAGNITUDE MEASURED AS THE AIRCRAFT WAS HOVERING 25 FT AGL AT 70 FT FROM THE SENSORS